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Climate Coalitions in an Integrated Assessment Model

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Abstract. An analytically tractable approximation of a numerical model is used to investigate coalition formation between nine major world regions with regard to their policies for greenhouse gas emission reduction. Full cooperation is not individually rational. Assuming non-transferable utility, side payments do not ensure full cooperation either. Without side payments, the largest stable coalitions are small and consist of similar regions. With side payments, the largest stable coalitions exclude either the main culprits or the main victims of climate change. In all cases, optimal emission control is modest.

Key words: climate change, coalition formation, LQ games, optimal emission control

1. Introduction

Climate change is a complex problem. For a proper understanding (hopefully leading to informed decisions), complicated models need to be build. There is lttle special about that, were it not that the cause-effect chain of climate change crosses the terrains of many disciplines, including physics, chemistry, ecology, economics, and political science. An analysis of climate change thus combines, perhaps even integrates the scientific traditions of various academic disciplines. Models supporting such analyses face a similar challenge. A number of individuals and groups have taken up this challenge and started building what are now known as integrated assessment mdoels of climate change. These models link together relevant 'disciplinary models'. There are numerous ways of doing this, and about 25 different models have emerged. Integrated assessment models come in sorts, however. The survey in Chapter 10 of the *Second Assessment Report of Working Group III* of the Intergovernmental Panel on Climate Change (Weyant et al., 1996) distinguishes two main groups: policy optimisation and policy evaluation models. The evaluation modellers take a policy proposal, run it through their system, and evaluate what comes out. The optimisation modellers do the same, but also rank the outcomes,

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and select the policy that is best (the definition of which is model-dependent and disputed). Optimisation is only possible by sacrificing model detail to increasing computational speed. Optimisation IAMs sacrifice lots of detail, but still need to be solved numerically. This allows one to analyse only a limited number of cases, particularly the more straightforward ones. Moreover, although the behaviour of the disciplinary components of the model is well-known, the behaviour of the coupled system is little understood.

This paper attempts to contribute a little to both problems. I try to derive an understanding of the interactions between the optimal emission reduction policies of (groups of) nations. I use this understanding to analyse the formation of coalitions between regions. The literature on optimal emission reduction is, so far, restricted to non-cooperative and fully cooperative policies (Escapa and Gutierrez, 1997; Eykmans et al., 1993; Fankhauser and Kverndokk, 1996; Hoel, 1994; Nordhaus and Yang, 1996; Peck and Teisberg, 1999). The literature on coalition formation in the context of climate change and other international environmental issues is, so far, restricted to analytical reasoning (Barrett, 1990, 1994; Bottean and Carraro, 1997; Carraro and Moricone, 1997; Carraro and Siniscalco, 1992, 1993; Chander and Tulkens, 1992; Chen, 1997), without much 'empirical' input. This paper tries to combine these strands of literature. The paper focuses on a policy optimisation integrated assessment model of climate change called the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)*, Version 1.5 (Tol, 1997a,b).

This paper follows this route. In Section 2, an analytically tractable approximation (linear-quadratic) of *FUND* is derived. This is used in Section 3 to look at the formation of coalitions bewteen the nine players involved. Section 4 extends this by allowing for all interregional capital transfers, which is not trivial as utility is non-transferable in *FUND*. Section 5 concludes.

2. An Analytical Approximation to FUND

Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Version 1.5, is in many respects an ordinary integrated assessment model of climate change. It captures the full cycle from population, to economic activity, to emissions, to changes in the atmospheric composition, to climate change, to its impacts, and then back to population and economy. *FUND* 1.5 also includes the effects of greenhouse gas emission reduction on conventional air pollution. Other integrated assessment models typically ignore these so-called secondary benefits. *FUND* covers the period 1990–2200 in time steps of one year. It distinguishes nine regions: OECD-America (OECD-A), OECD-Europe (OECD-E), OECD-Pacific (OECD-P), Central and Eastern Europe and the former Soviet Union (CEE&fSU), Middle East (ME), Latin America (LA), South and Southeast Asia (S&SEA), Centrally Planned Asia (CPA) and Africa (AFR). All component modules are simple and calibrated to reflect state-of-the-art knowledge. The overall behavior of the model mimics the consensus of the literature. The aim of the model is to calculate emis-

Table I. Costs and benefits of CO_2 emission reduction.

Region	Primary[a]	Secondary[b]	1% red.[c]	10% red.[d]
OECD-America	1.5	15.00	0.02	0.76
OECD-Europe	1.6	11.18	0.04	0.77
OECD-Pacific	3.8	4.02	0.06	0.97
Central and Eastern Europe and the former Soviet Union	–0.4	9.46	0.02	1.63
Middle East	5.5	0.56	0.01	0.60
Latin America	3.1	1.69	0.12	12.03
South and Southeast Asia	5.3	2.23	0.04	3.85
Centrally Planned Asia	–0.1	4.01	0.01	0.56
Africa	6.9	0.99	0.01	0.60

[a] Monetized impact (as percent of GDP) of a doubling of the atmospheric concentration of carbon dioxide on the current economy.
[b] Marginal benefits (as \$/tC) of greenhouse gas emission reduction on conventional air pollution.
[c] Total costs (as per cent of GDP) of a one per cent cut in carbon dioxide emissions.
[d] Total costs (as per cent of GDP) of a ten per cent cut in carbon dioxide emissions.

sion reduction strategies that balance the impact of climate change and the impact of emission abatement. To that end, all impacts of climate change and conventional air pollution are expressed in their monetary equivalents and, together with the costs of emission abatement, used to correct consumption and investment. Regional welfare is defined as the natural logarithm of per capita consumption minus per capita monetized, intangible damage of climate change and air pollution. Per capita consumption reflects the costs of emission reduction and the monetized, tangible damages of climate change and air pollution. *FUND*, Version 1.5, is presented in greater detail in Tol (1997a, b), and in the appendix. Some key parameters are displayed in Table I.

Impacts of emission reduction and climate change are balanced by maximising net present welfare. In the full model, this can be done both with full cooperation, and without any cooperation between the nine regions. Below, an approximate model is derived to study situations lying between non-cooperation and full cooperation. Non-cooperative optimal emission reduction equals the standard Nash-Cournot case, that is, each region maximises its net welfare, knowing the optimal emission reductions of the other regions. Non-cooperative optimal emission reduction differs from the business-as-usual (or no climate policy) scenario because the number of regions is only 9 (see Nordhaus and Yang, 1996, for a non-cooperative game with many more players). Cooperative optimal emission control follows from maximising the joint welfare of all regions together.

FUND is implemented in TurboPascal 7.0 for DOS. A third-generation language allows more flexibility than a fourth-generation one, such as GAMS.

Flexibility is needed if one is interested in performing simulation, optimisation, game-theoretic, and uncertainty analyses with the same model.

The optimisation algorithm is specific to *FUND*. The model is structured in such a way that there is a single optimum for both the cooperative and the non-cooperative case. In the cooperative case, the optimum is found by the method of steepest descent. Starting from zero emission reduction for all regions, emissions are reduced for that region that most increases global welfare. This is repeated until a maximum is reached. This process is repeated with decreasing step-size.

The non-cooperative case is slightly more involved. In the first iteration, given zero emission reduction for all other regions, optimal emission reduction is found for each region. Knowing that there is a single optimum, this is readily found by walking there with decreasing step-size. The optimal emission reductions of the first iteration are assumed for the other regions in the second iteration. This is repeated until the nth and $(n + 1)$th iteration yield the same answer; typically, n is small (5 or 6).

The structure of the *FUND* model differs from that of the other policy optimisation integrated assessment models of climate change. Opposed to what is common in this type of model, the accumulation of capital is not driven by optimisation, but based on an exogenous scenario. Experimentation with other IAMs, particularly Nordhaus's *DICE*, revealed that investments are hardly affected by climate change or emission reduction policies.[1] At the same time, calculating optimal investments requires time-consuming optimisation even for the no-intervention, business-as-usual scenario. *FUND* does not require that. It does not optimise but assumes investments.

A second difference is that *FUND* does not explicitly calculate the optimal emission reduction in each period of time. Rather, future emission reduction follows from the optimal reduction in the decade 1990–2000. Tol (1997a) shows that a fixed trajectory of emission reduction, varying only in its starting point, is a good approximation for a full intertemporal optimisation. The optimal trajectory is smooth and not very steep. There are two reasons for this. First, the energy module of *FUND* is very simple and indeed smooth. Second, the impacts of climate change depend more on the rate of climate change than on its level (cf. Tol, 1996).

Thus, per region, emission reduction policy can be described with a single number. Emission reduction can be set at any level – if the model is used in its simulation mode – or it can be set so as to maximise net present welfare – if the model is used in its optimisation mode.

These are the two crucial differences of *FUND*: it can evaluate policies without optimisation, and it can describe a policy with a single number. These features serve a goal. Optimisation requires that there is a single indicator to distinguish a good from a bad policy. This indicator is the net present welfare of a region. One is then interested in the mapping of the indicator that describes the policy to the indicator that evaluates the policy. Since *FUND* can run many scenarios in a short time, it is possible to visualise this mapping, even for the interactions between its

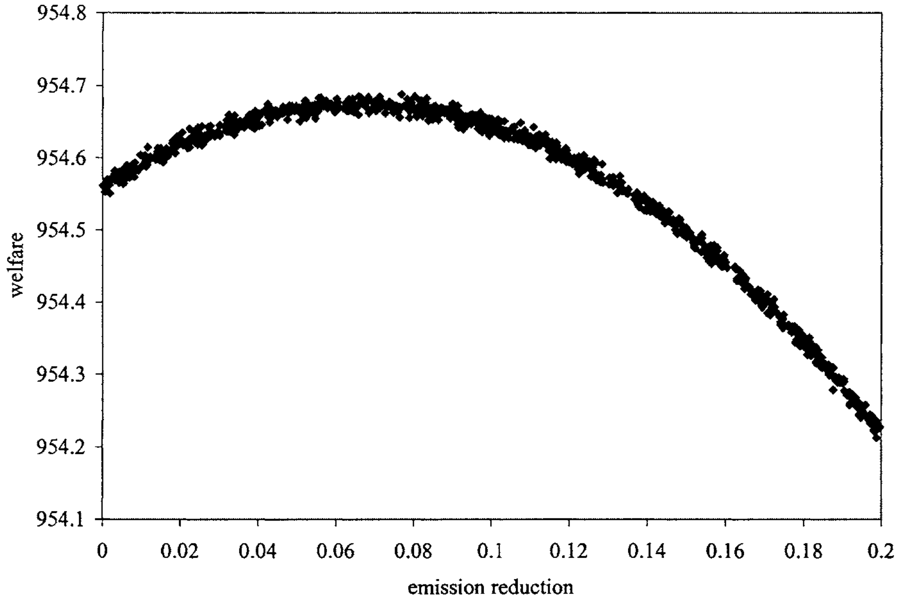

Figure 1. Net present welfare of OECD-America as a function of its emission reduction, with random variation of the other regions' emission control.

nine regions. Furthermore, this mapping can be captured with well-behaved analytical functions, so that the unwieldy numerical model has an analytically tractable counterpart.

The analytical approximation of *FUND* is derived in the following way. First, optimal cooperative and non-cooperative emission trajectories are calculated with the full model (cf. Tol, 1997a, b). Second, 1000 random emission abatement policies are evaluated. The random policies are selected from intervals encompassing the optimal reductions under cooperation and non-cooperation. Action and welfare indicators are saved and, in the third step, loaded into a statistical software package. Figure 1 depicts the relationship between emission reduction and welfare for OECD-America. There is clearly an optimum. The noise around what appears to be a smooth curve is the influence of the other regions' actions on the welfare of OECD-America. This noise is not large because OECD-America is little vulnerable to climate change (which is the only interaction between regions). Figure 2 displays the same relationship for Africa, which is muchj more vulnerable to climate change; consequently, its welfare is far more dependent on other regions' actions.

$$W_j = \alpha_j + \sum_i \beta_{j,i} R_i + \gamma_j R_j^2 \tag{1}$$

where W denotes net present welfare, R emission reduction, and j en i indicate the nine regions. Equation (1) explains more than 99.9% of the variations in welfare in all regions (cf. Table II) – this is so high because the number of observations is

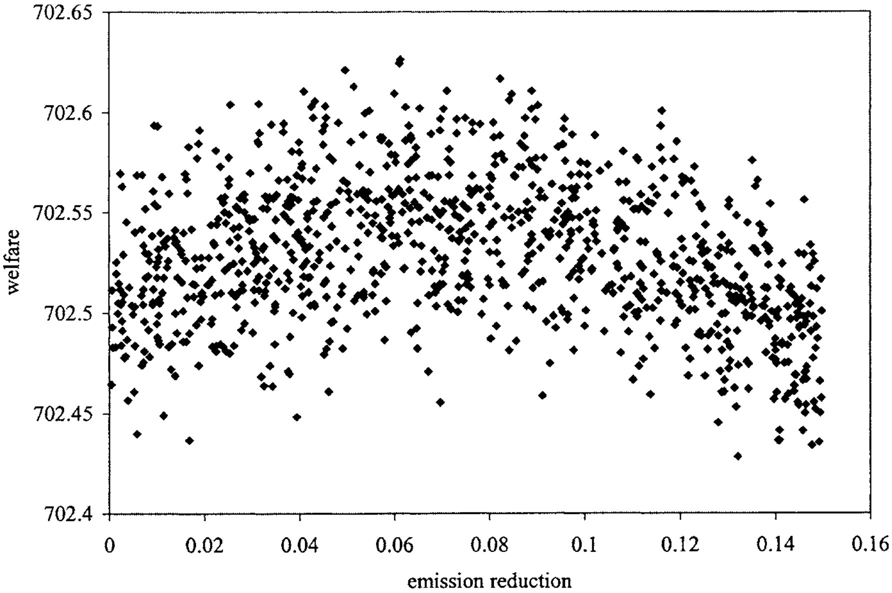

Figure 2. Net present welfare of Africa as a function of its emission reduction, with random variation of the other regions' emission control.

1000. Note that (1) is not a reaction curve; instead, (1) gives regional welfare as a function of emission reduction in each region.

The fourth step calculates optimal emission reductions. Equation (1) is a very convenient form, in fact, it is a linear-quadratic (LQ) game. The optimal solution without cooperation is simply $-\beta_{jj}/2/\gamma_j$, which is a maximum if $\gamma < 0$. To a first approximation, there is no interaction between the regions. The non-cooperative solution of the analytical approximation is indistinguishable from the numberical solution fo the full model (cf. Table III). Cooperation between regions can be profitable if region j does a little more for the benefit of region i and *viceversa*. The optimal reduction of region j, cooperating with region i, is $-(\beta_{jj} + \beta_{ij})/2/\gamma_j$, where β_{ij} is the influence of region j's emission reduction on region i's welfare. If region k joins the coalition, region j changes its emission reduction by $-\beta_{kj}/2/\gamma_j$, and so on for other regions joining. The fully cooperative solution of the analytical approximation again closely correspond to the numerical solution of the full model (cf. Table III). Since the LQ approximation is satisfactory for the cooperative and non-cooperative scenarios, it is assumed that the approximation is acceptable for all other possible coalitions as well.

3. Coalitions in *FUND*

Table II displays the βs and the γs of Equation (1). Interestingly, the βs and have mixed signs. Central and Eastern Europe and the former Soviet Union and

Table II. Influence of emission reduction by region ⟨column⟩ on the welfare or region ⟨row⟩. Standard deviations are given in parentheses.

	OECD-A	OECD-E	OECD-P	CEE&fSU	ME	LA	S&SEA	CPA	AFR	γ	R^2
OECD-A	3.4131[a]	0.0729	0.0319	0.0829	0.0229	0.0946	–0.0270	0.0556	0.0227	–25.6179[b]	0.9999
	(0.0023)	(0.0008)	(0.0011)	(0.0008)	(0.0006)	(0.0011)	(0.0011)	(0.0006)	(0.0008)	(0.0112)	
OECD-E	0.0836	1.0334	0.0297	0.0758	0.0128	0.0383	–0.0143	0.0511	0.0103	–16.8901	1.0000
	(0.0002)	(0.0009)	(0.0004)	(0.0002)	(0.0002)	(0.0003)	(0.0004)	(0.0002)	(0.0002)	(0.0060)	
OECD-P	0.0825	0.0654	–1.2545	0.0742	0.0197	0.0359	–0.0678	0.0506	0.0210	–16.7772	0.9999
	(0.0005)	(0.0006)	(0.0038)	(0.0006)	(0.0005)	(0.0009)	(0.0009)	(0.0005)	(0.0006)	(0.0374)	
CEE&fSU	–0.0380	–0.0292	–0.0124	4.2234	–0.0075	–0.0132	–0.0128	–0.0218	–0.0063	–41.4530	1.0000
	(0.0001)	(0.0002)	(0.0002)	(0.0006)	(0.0001)	(0.0002)	(0.0002)	(0.0001)	(0.0002)	(0.0039)	
ME	0.2491	0.1951	0.0862	0.2149	7.6000	0.1061	0.1042	0.1458	0.0559	–15.0527	0.9998
	(0.0004)	(0.0005)	(0.0008)	(0.0005)	(0.0038)	(0.0008)	(0.0008)	(0.0004)	(0.0005)	(0.0076)	
LA	0.3604	0.2820	0.1260	0.3148	0.0836	1.2611	0.1587	0.2133	0.0843	–255.6904	1.0000
	(0.0007)	(0.0009)	(0.0013)	(0.0009)	(0.0007)	(0.0052)	(0.0013)	(0.0007)	(0.0009)	(0.0508)	
S&SEA	0.5063	0.3969	0.1765	0.4425	0.1170	0.2220	2.6919	0.2999	0.1192	–82.2470	0.9999
	(0.0008)	(0.0010)	(0.0015)	(0.0010)	(0.0008)	(0.0015)	(0.0060)	(0.0008)	(0.0016)	(0.0582)	
CPA	–0.0636	–0.0480	–0.0174	–0.0404	–0.0067	–0.0084	–0.0091	10.0896	–0.0007	–9.5829	1.0000
	(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0001)	(0.0002)	(0.0002)	(0.0025)	(0.0002)	(0.0023)	
AFR	0.3579	0.2803	0.1237	0.3077	0.0802	0.1513	0.1492	0.2091	1.5669	–11.0143	0.9993
	(0.0006)	(0.0007)	(0.0011)	(0.0007)	(0.0005)	(0.0011)	(0.0011)	(0.0006)	(0.0029)	(0.0186)	

[a] $\beta_{1,1}$ in Equation (1).
[b] γ_1 in Equation (1).
Source: Own calculations.

Table III. Cooperative and non-cooperative optimal emission reduction[a] according to the full model, FUND1.5, and its approximation, Equation (1).

Region	Non-cooperative		Cooperative	
	Full model[c]	Approximation	Full model[c]	Approximation
OECD-A	0.0700	0.0666	0.1000	0.0966
OECD-E	0.0300	0.0306	0.0700	0.0666
OECD-P	0.0300	0.0000	0.0000	0.0000
CEE&fSU	0.0500	0.0509	0.0700	0.0687
ME	0.2500	0.2524	0.2600	0.2631
LA	0.0000	0.0025	0.0000	0.0033
S&SEA	0.0200	0.0164	0.0200	0.0182
CPA	0.5300	0.5264	0.5800	0.5788
AFR	0.0700	0.0711	0.0800	0.0850

[a] Percent emission reduction from the current baseline emissions.
[b] In the non-cooperative optimum, regions maximise regional net present welfare knowing the other regions optimal emission reduction. In the cooperative optimum, the sum of regional welfare is maximised.
[c] The numerical optimum is found with an accuracy of two digits, i.e., a hundredth of a percent.
Source: Tol (1997b) and own calculations.

Centrally Planned Asia do approve of other regions abating emissions. The reason is that these regions (are assumed to) benefit from climate change (Fankhauser, 1995; Tol, 1995). They do reduce their own emissions due to conventional air pollution. Some other βs are negative too. This is probably a statistical fluke, despite the high significance of the parameter estimates OECD-Pacific is the only region which seeks to increase its emissions. Emissions are capped with business-as-usual emissions.

As the optimal control for each possible coalition is now known in closed form, the entire coalition space can be searched in a relatively straightforward manner. Consider first the case without interregional side payments. All coalitions, starting with the largest, are analysed as to whether their members have an incentive to leave, that is, whether a region can increase its welfare by acting on its own. It appears that only a few, small coalitions are internally stable.[2] Note that, since the search starts with the full coalition, the largest coalitions are externally stable as well, that is, no other region would seek to join the coalition. Note also that, in an LQ-game, the stability of the coalition is unaffected by the question of whether or not the non-members cooperate with each other.[3] The total number of internally stable coalitions is 8, the largest coalitions have 3 members. The internally stable coalitions are:

{OECD-P, LA, S&SEA}
{OECD-E, CEE&fSU, CPA}
{OECD-A, CEE&fSU, CPA}
- *{OECD-A, OECD-E}*

{OECD-E, CPA}
- *{CEE&fSU, CPA}*
- *{ME, AFR}*
- *{LA, S&SEA}*

The coalitions in *italics* are the ones that together uniquely form the bargaining set, nucleolus and kernel (cf. Friedman, 1991, for definitions). That is, OECD-America and OECD-Europe prefer to be together rather than with the (former) Communist countries. Latin America and South and Southeast Asia are better off without OECD-Pacific. The expected outcome of international negotiations thus entails four small coalitions and one atom. Barrett (1990, 1994), Carraro (1998), Carraro and Moricone (1997), Carraro and Siniscalco (1992, 1993), Chen (1997), Eyckmans et al. (1993), Hoel (1994), Nordhaus and Yang (1996), and Tol (1997, 1999a,b) established earlier that the grand coalition is unstable. Based on analytical reasoning, Barrett and Carraro argued earlier that a number of smaller coalitions may be stable.

The stability of coalitions depends in a non-trivial and ambiguous manner on the parameterization of the underlying model. For instance, consider the case in which player j decides whether or not to cooperate with player k. The change in welfare of player j is:

$$\Delta W_j = \frac{\beta_{kj}}{2}\left(\frac{\beta_{kj}}{2\gamma_j} - \frac{\beta_{jk}}{\gamma_k}\right) . \tag{2}$$

All four parameters in (2) would change if the parameterization of the model changes. It is therefore impossible to say *a priori* what the impact on the stability of coalitions would be. Elaborate re-estimation of (1) is the only way out.

If the climate sensitivity is doubled from 2.5 °C temperature increase for a doubling of the atmospheric concentration of carbon dioxide to 5 °C, the number of stable coalitions declines. There is more at stake, and so potential coalition partners are better scrutinised. The kernel (etc.) remains largely the same, although the cooperation between Central and Eastern Europe and the former Soviet Union and Centrally Planned Asia breaks up. The internally stable coalitions are in this case:

{OECD-P, LA, S&SEA}
- *{OECD-A, OECD-E}*
- *{ME, AFR}*
- *{LA, S&SEA}*

If the climate sensitivity is halved to 1.25 °C for doubled CO_2, the number of internally stable coalitions increases:

{OECD-A, OECD-E, CEEE&fSU, CPA}
{OECD-A, OECD-P, CEEE&fSU, CPA}
{OECD-E, OECD-P, CEEE&fSU, CPA}
{OECD-A, OECD-E, CPA}
{OECD-P, CEEE&fSU, CPA}
{OECD-P, LA, C&SEA}
- *{OECD-A, OECD-E}*
{OECD-A, CEEE&fSU}
{OECD-A, CPA}
{OECD-E, CEEE&fSU}
{OECD-E, CPA}
- *{CEE&fSU, CPA}*
- *{ME, AFR}*
- *{LA, S&SEA}*

The kernel (etc.) remains the same. Centrally Planned Asia prefers a coalition with Central and Eastern Europe and the former Soviet Union over one with OECD-America and/or OECD-Europe. The (former) Communists prefer to be together rather than sticking with two OECD regions.

In all three cases, similar regions tend to cluster together, the main similarity being the impacts of climate change. Centrally Planned Asia and Central and Eastern Europe and the former Soviet Union both benefit from climate change, OECD-Europe and OECD-America are a little vulnerable, Latin America and South and Southeast Asia are modestly vulnerable, and Africa and the Middle East are very vulnerable to climate change. Increasing the odds, i.e., increasing the severity of climate change, reduces the incentives of regions to cooperate.

4. Interregional Capital Transfers

In *FUND*, interregional capital transfers are not straightforward, *FUND* optimises net present welfare, which is not-transferable. Capital can be transferred, but welfare is non-linear in capital. For small transfers, the relationship between capital transfers and welfare is:

$$K = Y_{1990}(e^{\Delta W/188.6} - 1) , \tag{3}$$

where K denotes the capital transfer, Y_{1990} GDP in 1990 and ΔW the change in welfare (cf. Tol, 1997a,b). The 'one-size-fits-all' nature of (3) comes about because the regions have the same pure rate of time preference. Population and economic growth rates differ, but this effect is exactly cancelled by the induced differences in discount rates. Thus, changes in the net present welfare due to capital transfers are determined by the pure rate of time preference (1%) and the time horizon (100 years) – 88.6 derives from this. The exponential comes about because welfare is the natural logarithm of income.

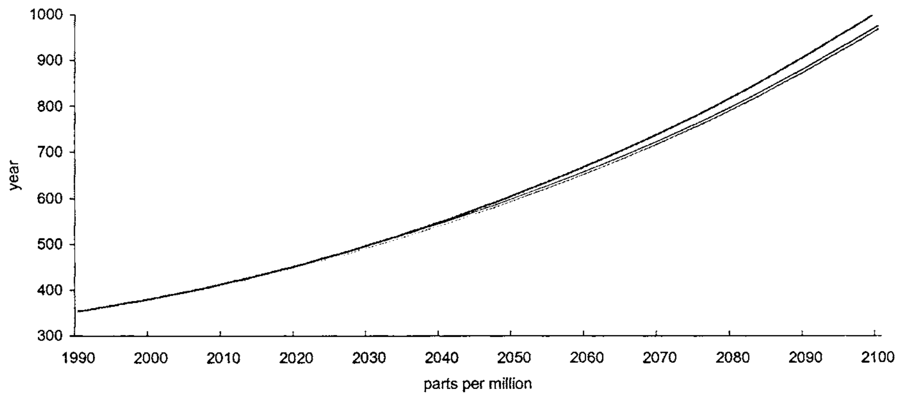

Figure 3. The atmospheric concentration of carbon dioxide according to, from to bottom, business-as-usual, full non-cooperation, kernel without side payments, kernel with side payments, and full cooperation.

Because of the nonlinearity of Equation (3), a coalition that improves welfare for the total of its members but not for each individual does not automatically generate sufficient side payments for its sustenance. In this case, the poor, vulnerable regions benefit most from cooperation. Their welfare gains, translated into money, are not sufficient to convince the rich regions to emit less. A similar search procedure is used: starting with the largest coalition, all coalitions are analysed as to whether they can generate capital transfers to improve upon the kernel. The two largest such coalitions occur in the following solutions:

- *{OECD-A, OECD-E, OECD-P, CEE&fSU, ME, LA, CPA} {S&SEA} {AFR}*
  {OECD-A, OECD-E, OECD-P, CEE&fSU, ME, LA, S&SEA, CPA, AFR} ,

where the one in *italics* is preferred by all regions bar OECD-America and OECD-Europe, which are compensated. Note that South and Southeast Asia and Africa also prefer the coalition which excludes them. The outcome is the same with climate sensitivity doubled or halved. Interestingly, either the two most vulnerable and pooresth regions (demanding most emission reduction while generating least transfers) are excluded, or the two largest and richest regions (emitting most while demanding high compensation for reductions). A similar grouping can be observed in the case without capital transfers. In that case, the (former) Communist regions, both benefiting from climate change, also cling together.

5. Conclusions

Figure 3 displays the trajectories of carbon dioxide concentrations in the atmosphere, for the business as usual, non-cooperative, kernel, capital transfer, and full cooperative (note: unstable) solutions. Differences are small. This is accentuated by Figure 4 which displays the corresponding global mean temperatures in

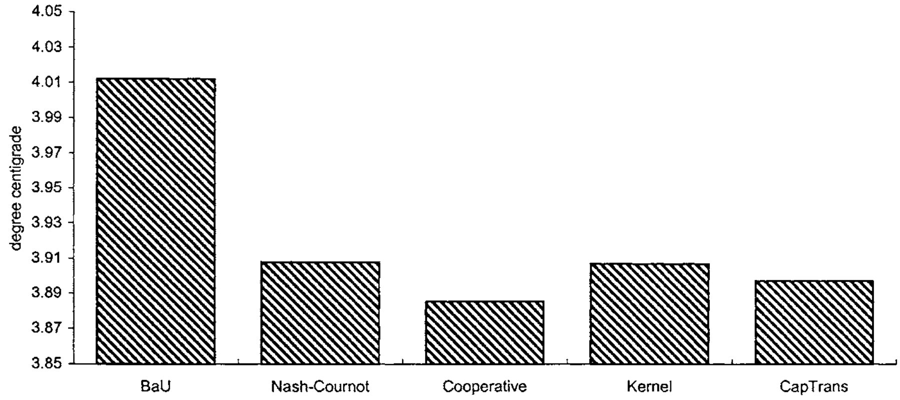

Figure 4. The global mean surface air temperature in the year 2100 according to, from left to right, business as usual, full non-cooperation, kernel without side payments, and kernel with side payments.

2100. The main message of this exercise turns out to be methodological, rather than policy-relevant. It is possible to use analytically tractable approximations of numerical integrated assessment models to analyse coalition formation. Fully cooperative welfare maximisation leads to modest greenhouse gas emission reduction. The global coalition is not stable, irrespective of the international side payments. Smaller coalitions lead to lower emission reductions. Without side payments, the largest stable coalitions are small (three regions) and consist of regions with similar characteristics. With side payments, the largest stable coalition excludes either the largest emitters or the most vulnerable regions.

Acknowledgements

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Notes

[1] Kaufman (1997) reaches a similar conclusion. Note that CETA (Peck and Teisberg, 1991, 1999) also uses this trick to speed up computations (Peck, personal communication, 1998).

[2] I do not analyse the stability of the coalition with respect to more than one member leaving at the same time. In the LQ-game, it does not matter whether members leave the coalition one at a time or simultaneously. To the defectors, it does matter whether they cooperate with each other or not. If stable, such sub-coalitions are identified in the search process.

[3] Cf. Note 2.

References

Barrett, S. (1990). The problem of global environmental protection. *Oxford Review of Economic Policy*, **6** (1), 68–79.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, **46**, 878–894.

Botteon, M. and Carraro, C. (1997). *Environmental Coalitions with Heterogenous Countries: Burden Sharing and Carbon Leakage*. Fondazione Eni Enrico Mattei, Milan.

Carraro, C. and Moricone, F. (1997). *International Games on Climate Change Control*. Fondazione Eni Enrico Mattei, Milan.

Carraro, C. and Siniscalco, D. (1992). The international dimension of environmental policy. *European Economic Review*, **36**, 379–387.

Carraro, C. and Siniscalco, D. (1993). Strategies for the international protection of the environment. *Journal of Public Economics*, **52**, 309–328.

Chander, P. and Tulkens, H. (1992). Theoretical foundations of negotiations and cost sharing in transfrontier pollution problems. *European Economic Review*, **36**, 388–398.

Chenz, Z. (1997). Negotiating an agreement on global warming: A theoretical analysis. *Journal of Environmental Economics and Management*, **32**, 170–188.

Escapa, M. and Gutierrez, M.J. (1997). Distribution of potential gains from international environmental agreements: The case of the greenhouse effect. *Journal of Environmental Economics and Management*, **33**, 1–16.

Eykmans, J., Proost, S. and Schokkaert, E. (1993). Efficiency and distribution in greenhouse negotiations. *Kyklos*, **46** (3), 363–398. Fankhauser, S. (1995), *Valuing Climate Change – The Economics of the Greenhouse*, EarthScan, London.

Fankhauser, S. and Kverndokk, S. (1996). The global warming game – simulations of a CO_2 reduction agreement. *Resource and Energy Economics*, **18**, 83–102.

Friedman, J.W. (1991). *Game Theory with Applications to Economics*, 2nd edn. Oxford University Press, Oxford.

Hoel, M. (1994), Efficient climate policy in the presence of free riders. *Journal of Environmental Economics and Management*, **27**, 259–274.

Kaufmann, R.K. (1997). Assessing the DICE model: Uncertainty associated with the emission and retention of greenhouse gases. *Climatic Change*, **35**, 435–448.

Nordhaus, W.D. and Yang, Z. (1996). RICE: A regional dynamic general equilibrium model of optimal climate change policy. *American Economic Review*, **86** (4), 741–765.

Peck, S.C. and Teisberg, T.J. (1999). CO_2 emission control agreements: Incentives for regional participation. *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, 367–390.

Tol, R.S.J. (1995). The damage costs of climate change: Toward more comprehensive calculations. *Environmental and Resource Economics*, **5**, 353–374.

Tol, R.S.J. (1996). The damage costs of climate change: Towards a dynamic representation. *Ecological Economics*, **19**, 67–90.

Tol, R.S.J. (1997a). *A Decision-Analytic Treatise on the Enhanced Greenhouse Effect*. Vrije Universiteit, Amsterdam.

Tol, R.S.J. (1997b). On the optimal control of carbon dioxide emissions: An application of FUND. *Environmental Modeling and Assessment*, **2**, 151–163.

Tol, R.S.J. (1999a). Kyoto, efficiency, and cost-effectiveness: Applications of FUND. *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, 130–156.

Tol, R.S.J. (1999b). Time discounting and optimal control of climate change – application of FUND. *Climatic Change*, **41** (3–4), 351–362.

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J.A., Grubb, M.J., Parson, E.A., Richels, R.G., Rotmans, J., Shukla, P.R., Tol, R.S.J., Cline, W.R. and Fankhauser, S. (1996). Integrated assessment of climate change: An overview and comparison of approaches and results, in Bruce, J.P., Lee, H. and Haites, E.F. (eds). *Climate Change 1995: Economic and Social Dimensions – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.